

Effects of UAS Performance Characteristics, Altitude, and Mitigation Concepts on Aircraft Encounters and Delays

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Introduction of Unmanned Aircraft Systems (UAS) into positively controlled airspace may cause greater per-aircraft impact on the National Airspace System than existing traffic because UAS aerodynamic performance and mission types are often different from aircraft that typically fly in positively controlled airspace (i.e. commercial passenger traffic). This paper examines the impact new UAS operations will have on existing aircraft and measures that impact by the number of predicted conflicts and associated conflict resolution delays that occurred in fast-time simulation. The two conflict metrics are quantified as a function of the UAS altitude and cruise speed. Two mitigation approaches are also investigated: increasing horizontal separation requirements for UAS and “burdening” UAS with the responsibility to execute all resolution maneuvers when possible. Results indicate that en route conflict maneuver delay for existing traffic because of new UAS operations can be nearly eliminated by burdening UAS with the responsibility to execute conflict resolution maneuvers and maintaining the current en route horizontal separation requirement of five nautical miles from other aircraft.

Introduction

New Unmanned Aircraft Systems (UAS) possess a range of differences from traditional, manned aircraft that make applying existing regulations complex or impossible, differences that could cause significant impacts to the National Airspace System (NAS). The foremost difference between UAS and traditional aircraft, the lack of an onboard pilot in UAS, creates uncertainty in how to meet the requirement that pilots “see and avoid” other aircraft. Yet this is not the only UAS characteristic that currently limits the number and type of UAS operations in the NAS, and it is not even the most important distinction from manned aircraft in positively controlled airspace requiring instrument flight rules (i.e. Class A airspace). That is, even with a sense and avoid (SAA) capability similar to manned aircraft, the different mission types and performance characteristics of most UAS will continue to restrict their operations until the impact of such factors on the wider NAS is better understood. The authors believe that the key data missing from UAS-NAS integration discussions are the expected number of interactions that typical UAS missions will have with existing traffic, the ability of UAS to avoid delaying commercial operations at a range of speeds and altitudes, and the amount of delay that will be incurred by current users of the airspace because of these novel UAS operations. The first and second metrics impact air traffic controllers’ workload and, therefore, may affect the safety and capacity of the NAS, while the second and third metrics bear on the trajectory efficiency of NAS users.

The original contributions of the research reported in this paper are the quantification of the effects of typical UAS mission and performance characteristics on existing NAS traffic, and evaluations of candidate procedural approaches for mitigating these effects. Several concepts for reducing UAS impact on existing operations have been proposed, including separating UAS with larger horizontal separation buffers to accommodate possible

communication latencies [Lacher et al., 2010] and having UAS always cede the right-of-way to manned aircraft [Weber and Euteneuer, 2010]. This latter concept may be viewed as a variation on more traditional delegated separation concepts. Unlike previous investigations of UAS impacts on the NAS, this paper reports the rate of conflicts and conflict resolution delays attributable to two medium-altitude, long-endurance UAS missions as a function of altitude and cruise speed. This paper also presents metrics on the efficacy of two approaches to reducing this impact on existing traffic. This study is the first to quantify the effects of these variables in simulations with thousands of UAS flight hours, millions of manned aircraft flights, and tens of thousands of conflicts between the two. The resulting metrics should help UAS mission planners and stewards of the NAS to determine which combinations of UAS flight profiles and performance characteristics have an acceptable impact on existing operations and which should be avoided. The metrics also quantify some of the benefits and costs of proposed concepts to minimize impact on existing NAS users, whether altering right-of-way rules or enforcing larger horizontal separation buffers for specific classes of operations.

The next section will describe research relevant to the problem of introducing UAS to the NAS. This background is followed by a section on overall experiment design, including the simulation system, conflict detection and resolution algorithm, UAS and background traffic scenarios, and data collection procedures. The fourth section presents results on the impact that UAS have on manned traffic as a function of UAS speed and altitude and how two proposed mitigation approaches can reduce that impact. The final section outlines conclusions and next steps.

Background

Investigation of the impact that larger numbers of operations typical of, but not unique to UAS will have on the NAS, has been limited, primarily because the simulation tools available to do so are not widespread. Most research on UAS integration with the NAS has focused on either the requirements for or design of an SAA system [Willis et al., 2013] [Chen et al., 2009] or laid out a concept of operations for UAS-NAS integration.[US Department of Defense, 2011; DeGarmo and Maroney, 2008; Anonymous, 2010]. While both of these areas are necessary to achieve the goal of seamless integration, they are insufficient because they do not address the airspace impact of additional, non-point-to-point operations. These operations, which frequently include loitering over an area for long periods of time, and performance, which is usually slower and may be less maneuverable than traditional aircraft, could be accommodated in the same ways that special missions like aerial surveying are today. The impact of such missions and performance characteristics on the NAS is, therefore, not unique to UAS, but the need to study their impact is being driven by the projected increase in number of UAS flying such missions. A pair of studies investigated the effects of Global Hawk operations around Beale Air Force Base in northern California [Niedringhaus and Lacher, 2010; Ostwald and Hershey, 2007]. The studies presented local traffic characteristics near Beale, determined the number of encounters with background traffic expected for a single Global Hawk flight, the extra distance flown to avoid aircraft-to-aircraft encounters, and the predicted increase in controller workload due to these encounters. The impact of a single Global Hawk flight was found to be minimal, primarily because the traffic density in this area was quite low. Whether operations with different UAS in different locations will have similarly low impact is not known. Several experiments with human controllers investigated the workload increases that accompanied an increasing proportion of UAS in a sector. Those studies demonstrated that increased workload was largely due to lack of a UAS Reduced Vertical Separation Minimum (RVSM) capability, not a UAS-unique factor like the lack of an onboard pilot [Helleberg and Maroney, 2010]. The experiments also found UAS required several extra seconds

to execute air traffic control clearances than manned aircraft and showed controllers had difficulty recognizing and dealing with lost-link procedures [Kamienski et al., 2010]. These research efforts on the local impact of UAS operations and controllers' experiences with those aircraft would be complemented by studies of the NAS-wide impact that new UAS missions will have.

Experimental Design

This section describes the software utilities used to model NAS operations, UAS, and air traffic controller separation services. It also describes the experiment matrix and data collection procedures.

Simulation Platform

The Airspace Concept Evaluation System (ACES) [George, S. et al., 2011] was used to simulate NAS operations. ACES is a fast-time, agent-based simulation platform that uses four-degree-of-freedom equations of motion to model aircraft using information derived from the Base of Aircraft Data (BADA) [Nuic, A., 2010]. This aircraft-type-specific performance data together with guidance and navigation models allows the ACES trajectory engine to generate representative trajectories for many aircraft. These trajectories are deterministic and are used to generate pseudo radar tracks. For each pseudo radar track cycle the trajectories are used for conflict detection and resolution. Conflicts are detected geometrically by iterating through each pair of aircraft and calculating the closest point of approach. ACES has been shown to approximate actual NAS operation in terms of total system delay [Zelinski, S., 2005].

The main input to ACES is a file containing the flight plans for each flight to be simulated. The flight-plan file contains the aircraft type, arrival and departure airports, departure time, and waypoints of the route for each flight. To simulate current-day operations, Aircraft Situation Display to Industry (ASDI) [Volpe Center, 2000] data for any timespan can be converted to an ACES flight input file by using the last filed flight plan before takeoff as the desired route. While ACES supports the modeling of wind fields and a variety of types of uncertainty, those features were not included in this study.

Scenarios

This section describes the types of UAS modeled for the experiment along with their missions and the flight plans for all the other traffic in the NAS against which the UAS impact is measured.

UAS Models

For this study, two representative aircraft models were created to simulate the envelope of performance characteristics of UAS currently operating in Class A airspace. The lower-speed model is similar in performance to a Predator B (also known as MQ-9 Reaper), though the model was not derived directly from that vehicle. The model is capable of flying at true airspeeds between 90 and 160 kn and to pressure altitudes above 40,000 ft (also known as Flight Level 400 or FL400). The second, higher speed aircraft model is based on the Global Hawk (RQ-4). Its performance in ACES closely matches trajectory data gathered from NASA hurricane monitoring missions, which were also flown by an RQ-4. This aircraft model is capable of flying between 200 and 400 kn at altitudes up to FL600. Both aircraft were assumed to be RVSM "equipped," which is consistent with requirements for other aircraft flying in the region of airspace tested. Removal of this assumption has been shown to increase controller workload[Helleberg and Maroney, 2010] and was determined to be an

unnecessary complication of the existing experiment plan. Both aircraft models are also capable of conducting a standard-rate turn of three degrees of heading per second.

1.1.1. UAS Missions and Background Aircraft Flight Plans

Two UAS missions were selected for initial study out of the many dozens that have been proposed [SC-203, 2012; Anonymous, 2012], allowing a comparison of how different flight plans in different locations affect the NAS. The first was a wildfire reconnaissance mission flown by NASA over the western United States in 2007 [Ambrosia, et al, 2007]. The second mission was a representative military training flight over the mid-Atlantic states [MTSI, 2011]. Figure 1 shows flight paths for these UAS flights, and Table 1 summarizes the flight plan distance and flight time for the experimental conditions tested. These missions were simulated among actual traffic that flew in the seven experimental Air Route Traffic Control Centers (“Centers”) over 46 hours from June 7, 2011 to June 9, 2011 (Tuesday through Thursday). To aid in later comparisons of UAS-impacted operations, the distribution of cruise altitudes for background traffic is shown in Figure 2.



Figure 1. Flight plans evaluated

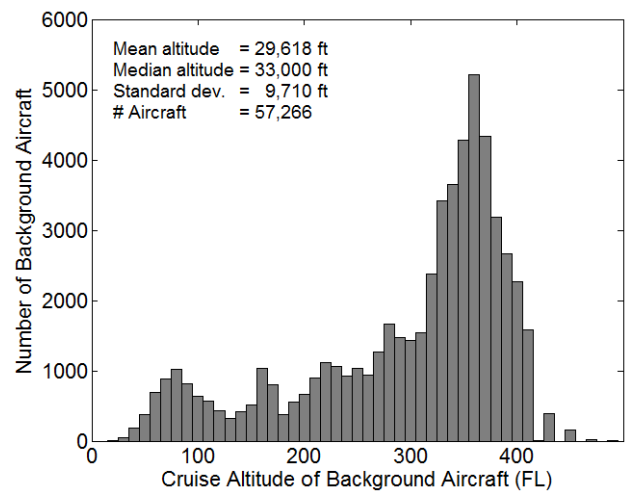


Figure 2. Distribution of cruise altitudes of manned aircraft

Table 1. Simulated UAS mission characteristics

	Flight Plan Distance (nmi)	UAS Cruise Speed, mission time (h)			
		100 kn	150 kn	250 kn	350 kn
Fire-Monitoring mission ¹⁸	3450	34.5	23	13.8	9.9
Mid-Atlantic training mission ¹⁹	750	7.5	5	3	2.1

Conflict Detection and Resolution Algorithm

The separation assurance system known as the Advanced Airspace Concept (AAC) [Erzberger, H., 2004] uses a strategic conflict resolution algorithm called the Autoresolver [Erzberger, H. et al., 2011],²¹ which may be used to reroute aircraft to achieve a desired horizontal or vertical separation requirement. The Autoresolver is a reasonable model for current separation practices because it employs conflict resolution maneuvers based on existing air traffic controller techniques for providing separation. The algorithm is designed to detect conflicts and provide resolutions for aircraft between 20 minutes and 2 minutes to loss of separation (LOS). The Autoresolver works by evaluating an array of maneuvers similar to those controllers use: path stretches, lateral route offsets, temporary climb and descent altitudes, step climbs and descents, direct-to's, and speed changes.

In most cases, path-stretch heading changes range from 5 to 120 degrees, altitude steps are attempted in 1,000 ft increments, and speed changes are between 25 kn slower and 15 kn faster. This set of resolutions has been shown to be effective in previous simulations with manned aircraft at traffic levels of up to three times current en route density [Kupfer, M. et al., 2008].

The Autoresolver used the same types of maneuvers on manned and unmanned aircraft for this experiment, but it was modified to study UAS-specific features. For example, a maneuver “preference” was added to the Autoresolver to allow the specification of which aircraft in a conflict is maneuvered. This feature may be used to investigate changes to existing right-of-way rules. Another new feature that was added to the Autoresolver was the assignment of aircraft-specific separation criteria. For example, manned aircraft could have the standard en route separation criteria of 5 nmi or 1000 ft, while in the same simulation, UAS would be required to stay 10 nmi or 1000 ft from all other aircraft. During the simulation, ACES detected aircraft conflicts and passed those to the Autoresolver, which returned a new conflict-free flight plan for one of the aircraft. ACES then updated the flight plan and simulated a new trajectory for that aircraft.

Experiment Matrix

The experiment matrix was designed to study the effect on manned aircraft of UAS flying the two mission types at a variety of altitudes and cruise speeds, many combinations of which are unusual for manned aircraft in today’s operations. The experiment also evaluated the efficacy of two approaches to mitigating the negative effects of these new UAS operations. A summary of the variables is given in Table 2. To understand the impact of different UAS altitudes and airspeeds, each mission was flown at five different flight levels and at four different airspeeds; the two lower airspeeds were always flown by the Predator B-like model described earlier, while the two higher airspeeds were always flown by the Global Hawk-like model. One test scenario contained a UAS at each of these flight levels and airspeeds for both missions, so there were 40 UAS in each scenario (20 Predator Bs and 20 Global Hawks). A single scenario with these 40 UAS comprised approximately 500 UAS flight hours.

Using the Autoresolver to maintain separation, three parameters were varied to evaluate concepts for mitigating UAS impact on manned aircraft. Four different values of required UAS horizontal separation were simulated, but to keep the size of the experiment matrix reasonable, the vertical separation requirement was always 1000 ft. Separation for manned aircraft was kept to 5 nmi. Also, three different conflict resolution look-ahead times were used; this is the earliest time before LOS that a conflict resolution maneuver may be sent to an aircraft. Finally, three different “burdening” cases for executing conflict resolution maneuvers were used. In the manned-burdened cases, conflicts between manned and unmanned aircraft are resolved by maneuvering the manned aircraft if any trajectory change by that aircraft can solve the conflict. Unmanned aircraft are maneuvered, if possible, in the UAS-burdened case. Whichever aircraft provides the most efficient maneuver (measured by the additional flying time required for the maneuver) is used for the no-burden case.

One scenario was run for each combination of the three mitigation conditions: UAS horizontal separation, resolution look-ahead time, and maneuver burdening. These 36 scenarios were also augmented by running a baseline case with no UAS.

Table 2. Experiment Matrix

Experiment Variable	Number of Conditions	Values of Conditions
Mission	2	Fire monitoring, military training
UAS Cruise Altitude (FL)	5	200, 250, 300, 350, 400
UAS Cruise Speed (kn)	4	100, 150, 250, 350
Horizontal Separation for UAS (nmi)	4	5, 10, 20, 30
Conflict Resolution Time (min)	3	8, 14, 20
Burdened Aircraft Type	3	UAS, manned, neither

Data Collection

A consistent set of metrics was collected across the 36 experimental scenarios and one baseline scenario. The primary metrics for NAS-impact are the number of conflicts between UAS and manned aircraft and the conflict resolution maneuver delay incurred by the manned aircraft because of conflicts with UAS. These metrics are compiled against the principal independent variables: UAS cruise altitude, UAS cruise speed, horizontal separation requirement, resolution look-ahead time, and whether the UAS or manned aircraft was burdened. Only aircraft-to-aircraft conflicts and the resulting delays were studied here; no traffic flow management initiatives, weather conditions, or other circumstances contributed to reroutes or delays.

Each of the 36 experiment scenarios included 57,266 manned flights, 40 UAS flights, and 494 UAS flight hours. There were 37,458 conflicts between manned aircraft and UAS over all 36 experiment scenarios (the large number of conflicts is because of the large horizontal separation requirements tested in some configurations). To aid in later comparisons of UAS-impacted operations, the distribution of conflict resolution maneuver delays for manned-to-manned conflicts in the seven simulation Centers is depicted in Figure 3. A negative delay means the aircraft saved flying time when executing a conflict resolution maneuver, for example bypassing an intermediate waypoint and going directly to a later waypoint. In the baseline case (no-UAS present), which generated Figure 2 and Figure 3, the average delay per manned-to-manned conflict was 15.7 s, and there were 9,743 of these conflicts over 17,300 manned flight hours. Together, these numbers imply that manned aircraft create delays for other traffic at a rate of 8.8 s per flight hour.

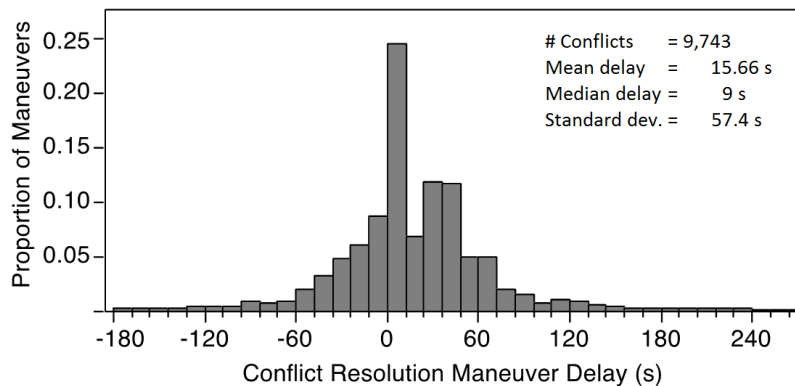


Figure 3. Conflict resolution maneuver delay distribution for baseline run with no UAS.

Results

This section presents metrics indicating the impact UAS will have on existing traffic and, where possible, compares the impact of one additional UAS with the impact of one additional manned aircraft. It also evaluates the effectiveness of two approaches to mitigating these effects: larger horizontal separation buffers and burdening the UAS with executing conflict resolution maneuvers whenever they encounter manned aircraft. In all sections, because the goal of this study is to understand the impact UAS operations will have on the provision of separation for manned aircraft, only those conflicts that manned aircraft were forced to resolve and the delays resulting from those conflicts are presented. Conflicts that were resolved by maneuvering the UAS are not part of the analysis.

The next two sub-sections investigate the effect UAS will have on manned traffic as a function of UAS speed and altitude. In these sections the UAS have priority over manned aircraft, which is generally consistent with controllers' reports that UAS are less predictable than manned aircraft and they maneuver UAS less. This is considered the baseline case. The third sub-section introduces the overall encounter and delay effects of the two mitigation approaches, demonstrating that significant delays occur when larger separation requirements are imposed on UAS. Because these large delays would likely be unacceptable to existing traffic, the fourth and fifth sub-sections concentrate on the speed and altitude effects of the burdening approach alone, though the sections do confirm that the trend apparent with all separation requirements is repeated with only the 5 nmi separation requirement.

Table 3. Independent variables evaluated in Section Impact of UAS Altitude on Manned Aircraft

Experiment Variable	Conditions in Section	Values of Conditions Evaluated in Section
Mission	0	Fire monitoring, military training
UAS Cruise Altitude (FL)	5	200, 250, 300, 350, 400
UAS Cruise Speed (kn)	0	100, 150, 250, 350
Horizontal Separation for UAS (nmi)	0	5, 10, 20, 30
Conflict Resolution Time (min)	0	8, 14, 20
Burdened Aircraft Type	1	UAS, manned neither

Impact of UAS Altitude on Manned Aircraft

This section presents NAS-impact results as a function of the altitude at which each LOS was predicted to occur (see Table 3). This impact is measured under a concept in which UAS have priority over existing traffic, i.e. the manned aircraft are burdened. Air traffic controllers report that under today's operations they prefer to maneuver manned aircraft rather than UAS because these aircraft respond more predictably than UAS,¹⁰ so these results represent the baseline impact UAS operations would have if this controller preference continued. Cruise altitude is an important independent variable to study because aircraft altitudes are not distributed uniformly across the airspace, and the characteristics of conflicts can change significantly with altitude (e.g. conflict geometry, approach speed). The impact of UAS operations on existing traffic is also not uniform with altitude, so particular cruise altitudes may be more suited to seamless UAS operations than others. The UAS cruise altitudes were at multiples of 5000 ft from FL200 to FL400, so conflicts at altitudes other than these represent vertical transitions for the UAS. Arrival traffic, defined as those aircraft within 20-min flying time of their destination TRACON (Terminal Radar Approach Control), are frequently constrained by neighboring flows

of traffic or metering times, so the conflicts are presented as a function of the manned aircraft flight phase in addition to the conflict altitude. The results in this section are drawn from those 12 scenarios in which the manned aircraft were burdened (one-third of the overall data set, totaling 480 UAS flights and 6000 UAS flight-hours).

The number of UAS-manned aircraft conflicts, broken down by the altitude of the UAS, is shown in Figure 4. Most notable in that figure is the large number of conflicts at lower altitudes (FL200 and FL250) even though most manned aircraft cruise between FL300 and FL400 (Figure 2). The mean altitude for background aircraft is 29,618 ft (Figure 2), while the average conflict altitude with UAS is 26,050 ft. As expected, the number of conflicts with arriving manned aircraft increases at lower altitudes, which contributes to the higher number of conflicts overall at FL200 and FL250. The conflict peaks at the experiment cruise altitudes (FL200, FL250, etc.) are simply due to the UAS flying at those altitudes for much longer times than they spent transitioning to or from the cruise altitudes.

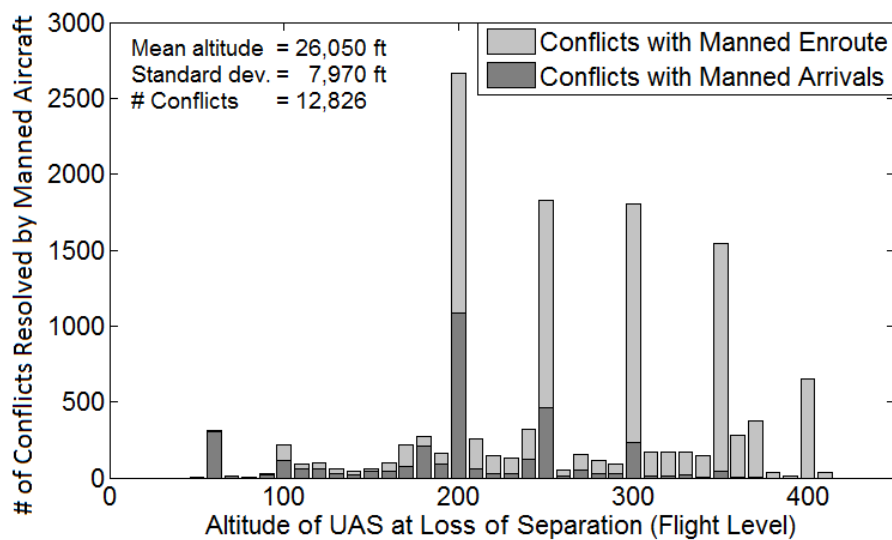


Figure 4. Number of UAS conflicts resulting in manned aircraft conflict resolution maneuvers as a function of UAS altitude for manned-burdened resolutions.

The delay to manned aircraft caused by UAS-manned conflicts is shown in Figure 5. This distribution of total delays by altitude shows that low-altitude conflicts are more numerous and they cause more delay than conflicts at FL300 and above. This can be seen by comparing the average altitude of all conflicts (26,050 ft) in Figure 4 with the delay-weighted altitude of conflicts (22,126 ft) in Figure 5. This effect is principally caused by the larger number of arrival conflicts at lower altitudes, which tend to cause more delay because arriving aircraft are constrained by neighboring flows of arrival traffic. These results suggest that UAS impact on existing traffic may be minimized by avoiding sections of airspace with large proportions of transitioning traffic, including those flight levels between 200 and 300. Further study of conditions with arrival metering should be conducted, because these operations are likely to further constrain the available resolutions and increase the expected delay.

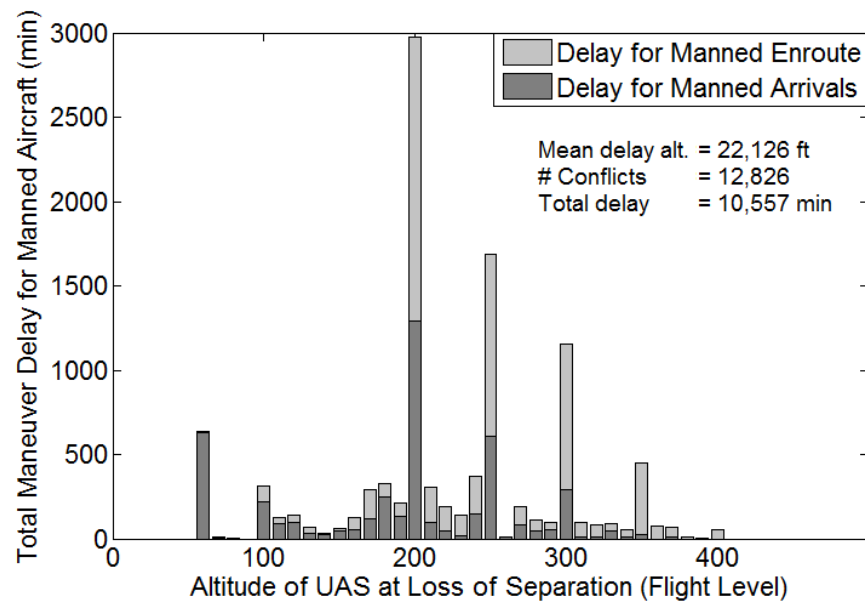


Figure 5. Total delay to manned aircraft as a function of UAS' altitude for manned-burdened resolutions.

Table 4. Independent variables evaluated in Section Impact of UAS Speed on Manned Aircraft

Experiment Variable	Conditions in Section	Values of Conditions Evaluated in Section
Mission	0	Fire monitoring, military training
UAS Cruise Altitude (FL)	0	200, 250, 300, 350, 400
UAS Cruise Speed (kn)	4	100, 150, 250, 350
Horizontal Separation for UAS (nmi)	0	5, 10, 20, 30
Conflict Resolution Time (min)	0	8, 14, 20
Burdened Aircraft Type	1	UAS, manned, neither

Impact of UAS Speed on Manned Aircraft

This section presents conflict and delay metrics as a function of UAS true airspeed. In these results, the UAS again have priority over existing traffic (the manned aircraft are burdened; see Table 4). One of the anticipated differences between future UAS operations and existing manned operations is the possibility that UAS could have lower cruise speeds than typically seen in Class A airspace. At lower cruise speeds UAS may disrupt more manned aircraft operations, and those conflicts may be more difficult for controllers to solve, potentially leading to a minimum-speed requirement above 18,000 ft in analogy with the 250 kn maximum speed under 10,000 ft. The UAS cruise speeds in this experiment were 100 kn, 150 kn, 250 kn, and 350 kn. Conflicts at speeds between these usually represent UAS still climbing to their cruise altitude. The results in this section are drawn from those 12 scenarios in which the manned aircraft were burdened (one-third of the overall data set, totaling 480 UAS flights and 6000 UAS flight-hours).

The total number of conflicts between manned aircraft and UAS as a function of the UAS speed is shown in Figure 6. The manned aircraft were burdened in this case, and all conflicts in that figure were resolved by the manned aircraft. The delay resulting from these maneuvers is shown in Figure 7. The total number of conflicts and delay is highest at the slowest cruise speed, but there is no clear trend at higher speeds. On a per-aircraft

basis, then, these figures suggest a 100 kn cruise speed has a disproportionately high impact on existing traffic. The UAS flying at 100 kn are, however, aloft longer than the UAS at higher speeds, so the per-flight-hour impact at 100 kn is about the same as the impact at 150 kn and lower than the impact at 250 or 350 kn. Figure 6 and Figure 7 confirm this result if one normalizes the conflict counts and delays by the UAS' cruise speeds. For example, the impact per flight hour can be calculated (to a constant) by multiplying the delay at 100 kn by 100 and the delay at 350 kn by 350; the normalized delay per flight hour is then 27 at 100 kn and 42 at 350 kn, an increase of 56%. Conflicts between low- and high-speed aircraft may increase airspace complexity and controller workload, but from the perspective of the number and delay of conflicts it does not appear that low-speed UAS have a disproportionate impact on existing operations. Additional research should determine the relationship between altitude and cruise speed and verify the somewhat counterintuitive result that low-speed UAS do not increase the number of conflicts or the delay per flight hour.

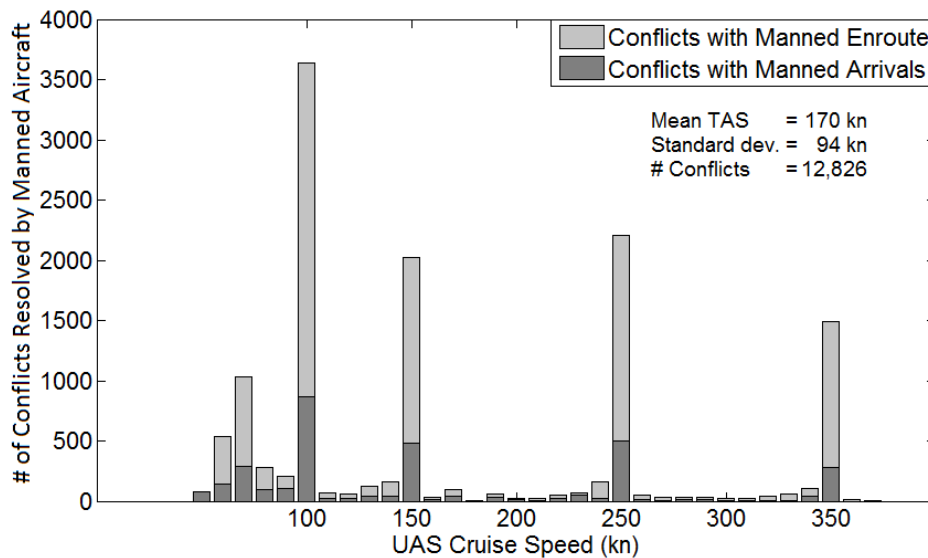


Figure 6. Number of UAS conflicts resulting in manned aircraft conflict resolution maneuvers as a function of UAS' speed for manned-burdened resolutions.

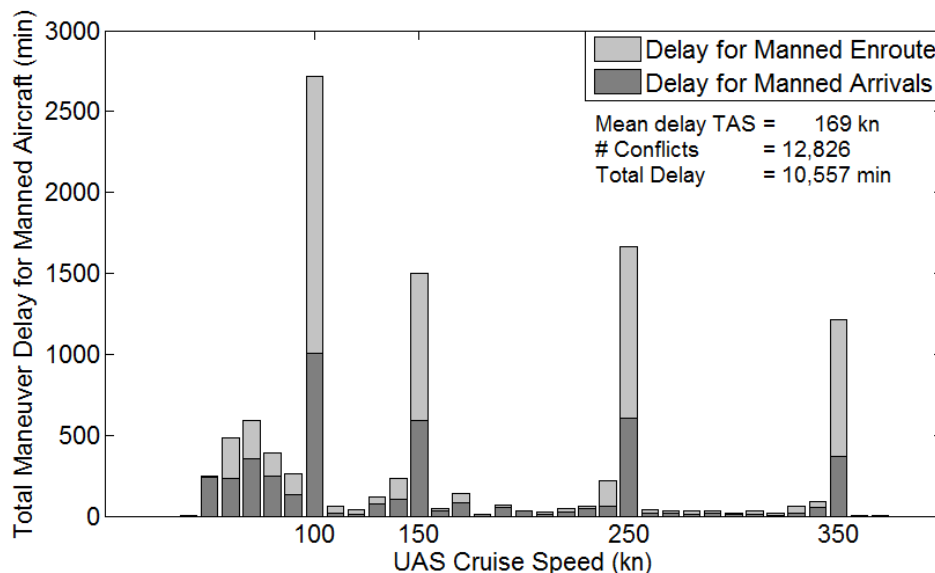


Figure 7. Total Delay to manned aircraft as a function of UAS speed for manned-burdened resolutions

Table 5. Independent variables evaluated in Section Mitigation Approaches

Experiment Variable	Conditions in Section	Values of Conditions Evaluated in Section
Mission	0	Fire monitoring, military training
UAS Cruise Altitude (FL)	0	200, 250, 300, 350, 400
UAS Cruise Speed (kn)	0	100, 150, 250, 350
Horizontal Separation for UAS (nmi)	4	5, 10, 20, 30
Conflict Resolution Time (min)	3	8, 14, 20
Burdened Aircraft Type	3	UAS, manned, neither

Mitigation Approaches: Separation Buffers and Burdened Aircraft

Two methods for reducing the impact of UAS operations on the NAS are presented in this section, each addressing a particular aspect of that impact: larger horizontal separation requirements would mitigate UAS communications and maneuvering latencies; burdening the UAS to resolve conflicts would reduce delays for manned aircraft. Each of these approaches draws on successful application in different airspace; the former is used in oceanic airspace where surveillance and communication are sparse, and the latter is applied under the right-of-way rules pilots must follow in avoiding different classes of aircraft. Whether either approach will be successful in en route and transition airspace remains unclear. The results in this section are presented in terms of the independent variables in Table 5

Figure 8 compares side by side the success rate of burdening UAS or manned aircraft; success means that the burdened aircraft was able to execute a conflict resolution maneuver, while failure means no successful maneuver was found and the non-burdened aircraft was required to maneuver instead. The data show that the success rate is over 95% for all cases when the manned aircraft is burdened, regardless of the UAS separation requirement. While resolution maneuvers are less efficient and cause more delay at larger separation requirements, there is nearly always a manned aircraft resolution available for UAS-to-manned aircraft conflicts. This result was consistent across all look-ahead times and the success rate was independent of that variable, which is surprising given that no uncertainties were simulated. This result is probably due to the nature of the Autoresolver algorithm itself, which was tuned to operate like a human controller around 10 minutes to loss of separation, and further algorithm refinements may find the look-ahead time to be an important parameter under these circumstances.

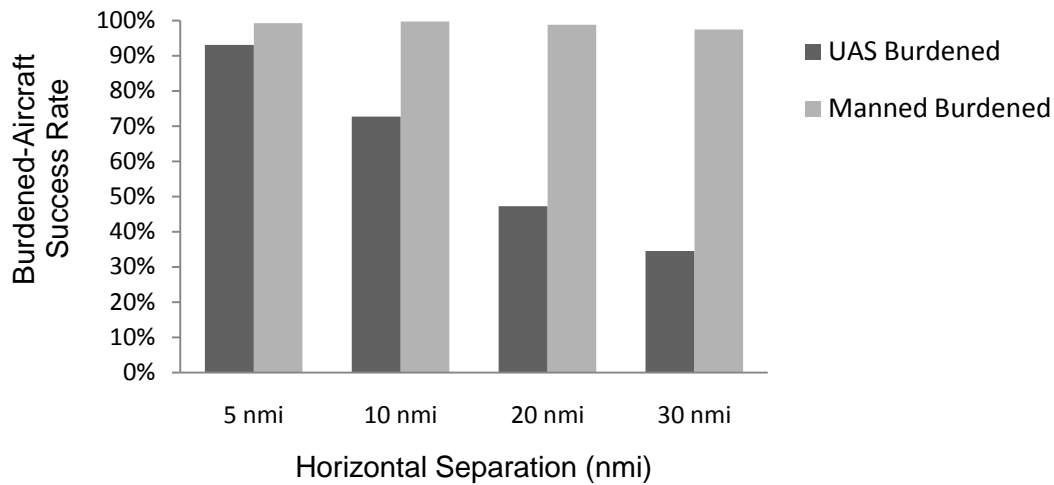


Figure 8. Success rate for the burdened aircraft in execution of resolution maneuver as a function of horizontal separation requirement..

The UAS success rate, in contrast to the manned success rate, tells a different story. With a required horizontal separation of 5 nmi the UAS is able to resolve conflicts in over 90% of conflict situations, only slightly lower than the manned success rate at this separation (97.8%). The ability of UAS to resolve conflicts gets progressively worse as the separation requirement is increased. With 10 nmi required separation, the Autoresolver can find an acceptable UAS resolution maneuver about 73% of the time, while the comparable manned rate was 98%. The success rate continues to drop at higher separation requirements: 46% for a horizontal separation of 20 nmi and 35% for 30 nmi. The manned aircraft were successful in resolving conflicts in over 97% and 95% of cases, respectively. This mitigation approach, when assessed only in terms of the success rate, suggests that larger separation requirements for UAS-to-manned aircraft conflicts will force the manned aircraft to maneuver more often because the generally slower UAS have difficulty getting out of the way. Any benefit to larger separation requirements in terms of longer allowable UAS communication latencies is probably outweighed by the additional maneuvering required of manned aircraft. These results suggest that larger horizontal separation requirements for UAS will have a detrimental effect on the NAS and manned aircraft operations. Burdening UAS to resolve conflicts, on the other hand, appears to be a viable approach to mitigating the impact of UAS when 5 nmi horizontal separation requirements are maintained.

Another important indicator of the viability of each mitigation approach is the absolute number of conflicts and conflict delay time. Figure 9 presents the total number of conflicts between a UAS and manned aircraft in which the manned aircraft was maneuvered. The number of maneuvers is decomposed according to the required horizontal UAS separation requirement, resolution look-ahead time, and burdened aircraft type. As a point of comparison for Figure 9, there were 9,743 conflict resolution maneuvers in the baseline run (no UAS flights). Each bar in that figure shows the *additional* manned aircraft maneuvers required when 40 UAS were flown against the background traffic. In general, the number of resolution maneuvers increases with the square of the separation standard. The number of maneuvers is lower—for a given separation standard—when the UAS is the burdened aircraft because manned aircraft must resolve the conflict only if the Autoresolver finds no way to resolve it with the UAS. In this sense, every conflict represented on the third row of Figure 9 represents a failure of the burdening concept to mitigate the impact of UAS operations on manned aircraft. For a required

separation of five nmi there are between nine and 134 additional manned maneuvers depending on the burdened aircraft type, a relatively small absolute increase. At 20 and 30 nmi, however, separation there are as many as 2887 more conflicts resolved by manned aircraft. The increase in conflicts at the largest separation requirements would cause a major impact on the efficiency of the airspace whether or not UAS are the burdened aircraft.

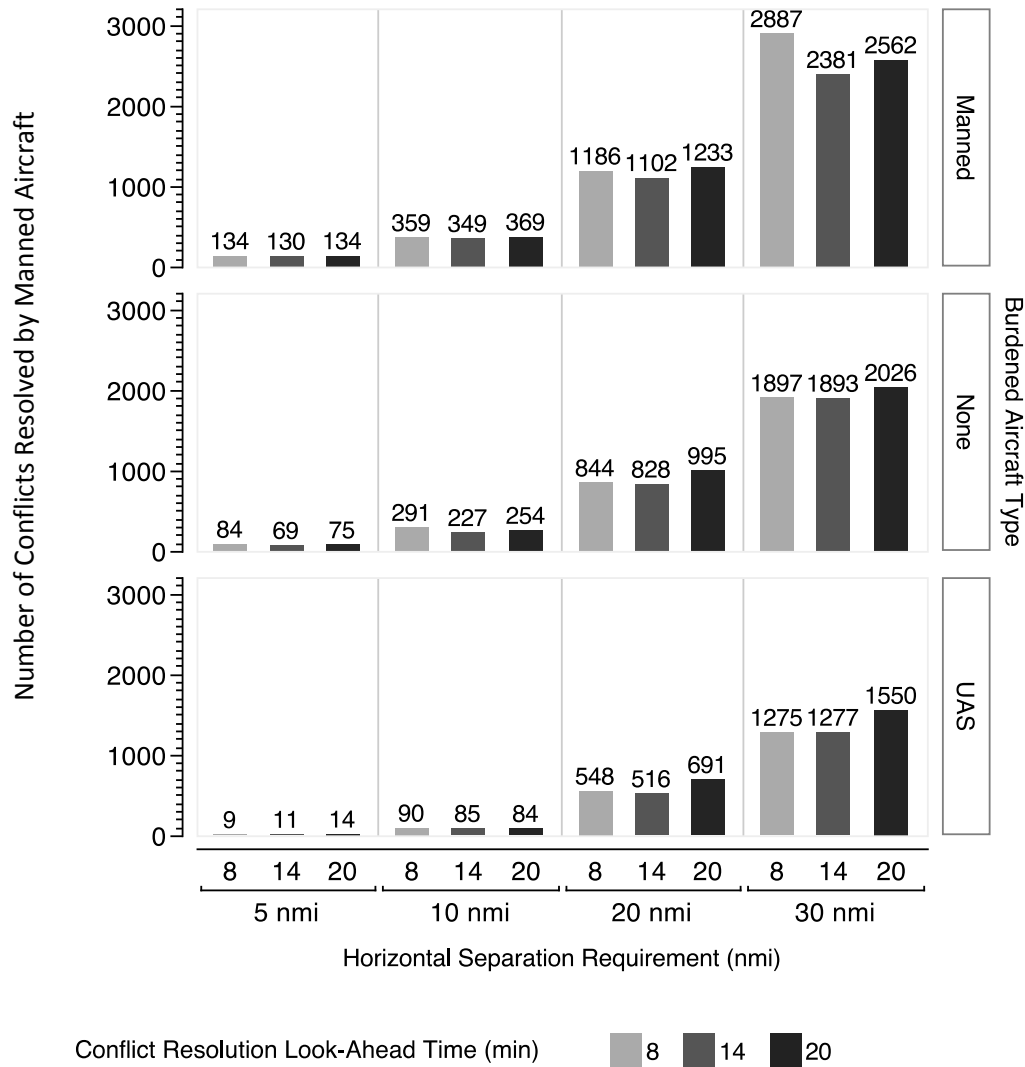


Figure 9. Number of conflicts in which manned aircraft were maneuvered as a function of resolution look-ahead time, horizontal separation requirement and burdened aircraft type.

The per-resolution maneuver delay is a useful metric when paired with the absolute number of conflicts because it quantifies the reduction in trajectory efficiency that comes with introducing UAS operations. Figure 10 shows the mean delay for resolution maneuvers executed by manned traffic to resolve a UAS conflict. To serve as a benchmark, resolution maneuvers from the baseline run with no UAS had an average of 15.7 seconds of delay per maneuver (see distribution in Figure 3). When the separation requirement is 5 nmi and neither aircraft is burdened or the manned aircraft is burdened, the mean delay of manned aircraft maneuvering to avoid UAS conflicts is between 4 and 9 seconds per maneuver, significantly outperforming the baseline. It is important to note that, although the individual conflicts are more efficient to resolve, the additional conflicts resolved by manned aircraft create a greater total delay to manned aircraft when they are burdened. This result is likely

because of the slower speeds of the UAS; an overtaking aircraft can easily avoid a slower one, and the difficult-to-resolve conflicts with aircraft at the same speeds and shallow encounter angles simply aren't present. By comparison, when the UAS is burdened and the separation requirement is 5 nmi, the mean delay for manned aircraft is about 80 seconds per conflict. The high average delay is explained by the difficulty manned aircraft have in resolving those very few conflicts that UAS cannot resolve when they are burdened and require only 5 nmi of separation; these are simply very difficult conflict situations to resolve efficiently. Only about ten such conflicts exist, and each results in an inefficient maneuver by a manned aircraft (including one 5.5 min delay maneuver). An example of this is a slow overtake situation with the UAS and several nearby aircraft that requires the manned aircraft to deviate a significant distance laterally to avoid all these neighboring aircraft. The total impact on manned aircraft from this condition is small, however, because of the small number of total conflicts.

The mean delay for manned aircraft resolving UAS conflicts increases with larger separation requirements. When requiring 10 nmi of separation for UAS conflicts, the delay is about 15 to 23 seconds per resolution for manned- and no-burden cases. Interestingly, the average delays for the 10 nmi UAS separation cases are about the same as the delay in the baseline, no-UAS case. This suggests that maneuvering manned aircraft to avoid UAS traffic at a separation standard of 10 nmi is about as inefficient as maneuvering manned aircraft to avoid other manned traffic at a standard of 5 nmi. This result is likely because UAS are flying more slowly than the manned traffic and so are more easily avoided by them. The mean delay for 20- and 30-nmi separation standards are quite poor, with 44 and 67 seconds of delay per resolution, respectively. This last result adds further evidence that increased UAS separation standards result in less-efficient manned aircraft operations: not only are there more conflicts at larger separations (Figure 9) and UAS are less able to resolve those conflicts when burdened (Figure 8), the eventual resolution maneuvers provide two to four times as much delay per resolution as the baseline runs when separation is larger than 10 nmi (Figure 10).

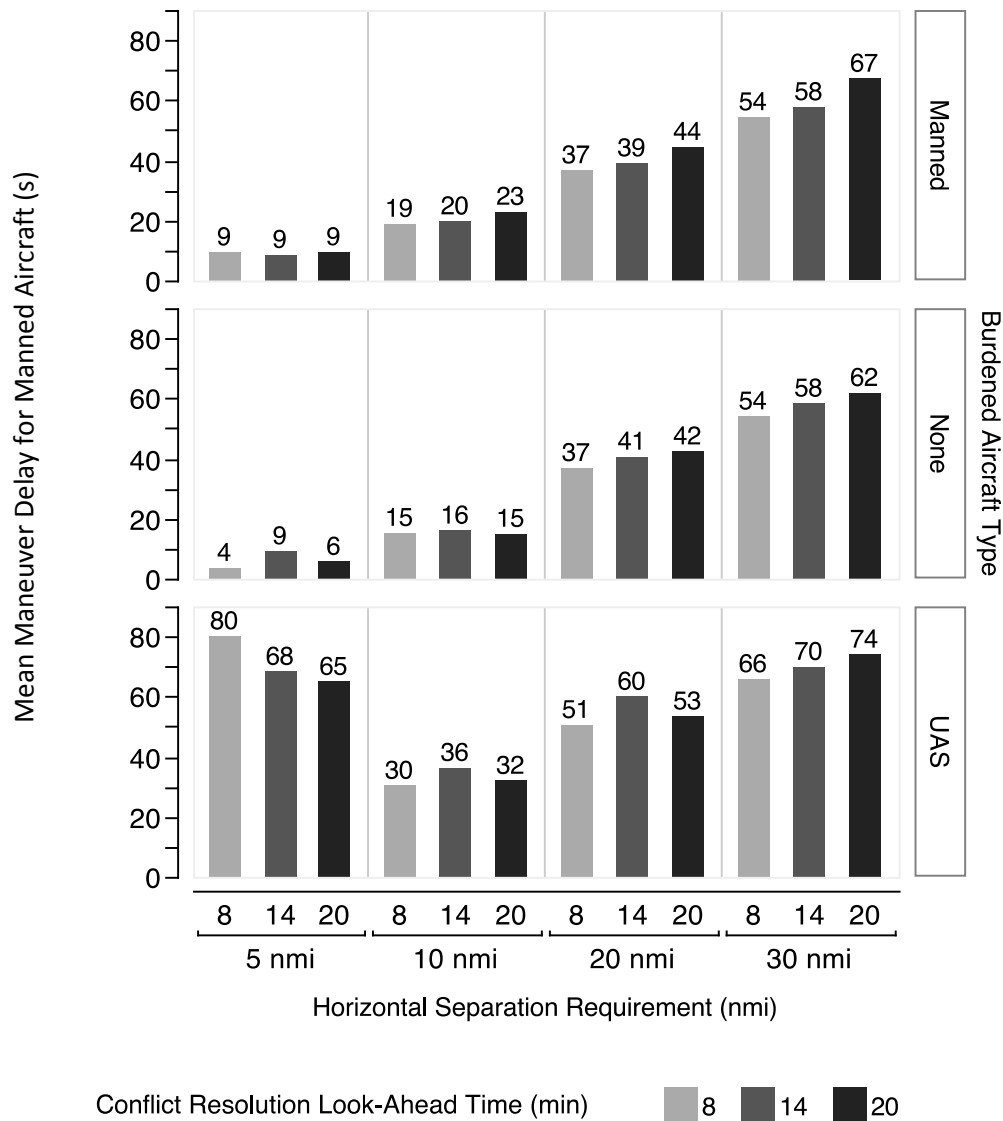


Figure 10. Mean delay for conflict resolution maneuvers in which manned aircraft were maneuvered as a function of look-ahead time, horizontal separation requirement and burdened aircraft type.

The mean resolution delay shows no clear trend across the look-ahead times because of two competing factors. In the absence of uncertainty, when resolutions can be executed earlier, the resulting trajectory is more efficient, which reduces the delay per resolution. When resolving earlier, however, the new trajectory must be conflict-free for a longer period of time, which may limit the number of successful resolution options. This factor increases the delay per resolution. Because the rate of each of these factors varies across experimental conditions no conclusion can be drawn directly from these data.

Table 6. Independent variables evaluated in Section Effectiveness of Mitigation Strategies: Altitude

Experiment Variable	Conditions in Section	Values of Conditions Evaluated in Section
Mission	0	Fire monitoring, military training
UAS Cruise Altitude (FL)	5	200, 250, 300, 350, 400

UAS Cruise Speed (kn)	0	100, 150, 250, 350
Horizontal Separation for UAS (nmi)	4	5, 10, 20, 30
Conflict Resolution Time (min)	0	8, 14, 20
Burdened Aircraft Type	2	UAS, manned <i>neither</i>

Effectiveness of Mitigation Strategies: UAS Altitude Dependency

This section investigates the effectiveness of the two mitigation approaches in reducing the number and delay of manned aircraft resolution maneuvers as a function of UAS cruise altitude (see Table 6). The data indicate that giving the burden of executing conflict resolution maneuvers to UAS is an effective way of reducing the impact on manned aircraft but that increasing the horizontal separation standard beyond 10 nmi is not.

The reduction in manned conflict resolution maneuvers achievable by burdening UAS as a function of UAS altitude is shown in Figure 11. The light gray bars in that figure show the distribution of altitudes UAS were at when they encountered a conflict they could not resolve and therefore resulted in a manned aircraft maneuver. An important result of this chart is the relative number of conflicts at different altitudes: the UAS was unable to resolve its conflicts with manned aircraft disproportionately often at the lower altitudes (especially FL200 and FL250) and during transition to or from cruise altitude (those bars between the peaks at 5000 ft intervals between FL200 and FL400). The degree to which conflicts were disproportionately at lower altitudes is indicated by comparison with the distribution of manned aircraft cruise altitudes shown in Figure 2: whereas most manned aircraft fly at or above FL300, the mean conflict altitude for UAS is at FL243. The apparent reason for the increasing inability of the UAS to avoid conflicts at lower cruise altitudes is because the manned aircraft are frequently transitioning altitudes here and, particularly at larger horizontal separation requirements, the UAS have difficulty avoiding aircraft that are climbing or descending. Operation of UAS at lower cruise altitudes in Class A airspace appears to make them less able to avoid conflicts with manned aircraft transitioning altitudes, shifting the burden of executing those conflict resolution maneuvers to the manned traffic.

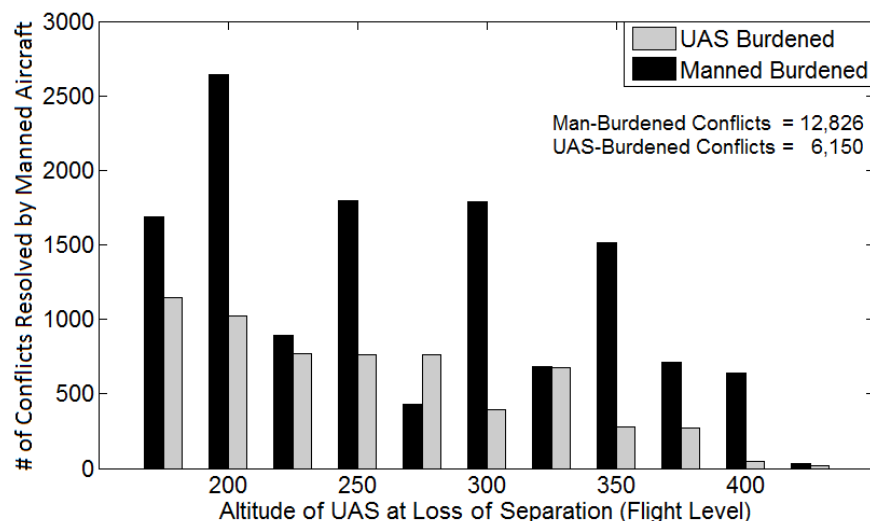


Figure 11. Manned aircraft maneuvers as a function of burdened aircraft type and UAS altitude.

A corollary to the conclusion of Figure 11 is that UAS are also less frequently able to separate themselves from manned aircraft when they (the UAS) are transitioning altitudes, not just when the manned aircraft are transitioning. This is only apparent when one compares the numbers in Figure 11 with the number of conflicts

involving UAS in which manned aircraft were required to resolve and did so successfully. Those statistics are shown in Table 7. That table shows the number of conflicts in which manned aircraft resolved UAS-manned conflicts as a function of whether the UAS was level in cruise or transitioning, and whether the UAS or the manned aircraft was burdened with executing the conflict resolution maneuver. Because the manned aircraft were able to resolve conflicts in 97% of all cases in which they were the burdened aircraft (see Figure 8), an indication of the degree to which UAS could solve conflicts in cruise or transition is obtained by comparing the relative number of conflicts in the two rows. In cruise, UAS were able to resolve about 72% of conflicts, while in transition UAS were successful for only 15% of conflicts. These results were extracted from simulation runs with all horizontal separation buffers and look-ahead times, so the equivalent numbers with today's separation standards (5 nmi) may be different. However, initial results suggest that this trend is present even with smaller separation requirements. UAS appear to be less able to reduce the impact of conflicts on manned aircraft when either they or the manned aircraft are transitioning altitudes, a problem that may be mitigated with careful route planning.

Table 7. Number of Manned Conflict Resolution Maneuvers and Inability of UAS to Resolve Conflicts

	UAS Level at Cruise	UAS Transitioning
UAS-Burdened, Manned-Resolved Conflicts	2280	3870
Manned-Burdened, Manned-Resolved Conflicts	8256	4570
% Conflicts Resolved by UAS	72.4%	15.3%

In the same way that burdening UAS with resolving conflicts reduces the number of manned aircraft maneuvers, burdening the UAS also significantly reduces the total delay to manned aircraft. Figure 12 shows the relationship between the UAS altitude and the reduction in manned aircraft delay: when the UAS is level at the cruise altitude the delay reductions are significant, but when UAS are transitioning the delays may actually be greater than in the manned-burdened condition. Why the delay to manned aircraft would ever be higher when UAS are burdened is unclear, but it is possible that those delays had previously been assigned to one of the level altitudes when manned aircraft were burdened. This finding warrants further investigation. Regardless of the distribution of delays by altitude, the total delay for manned aircraft can be reduced 38% by burdening UAS with resolving conflicts.

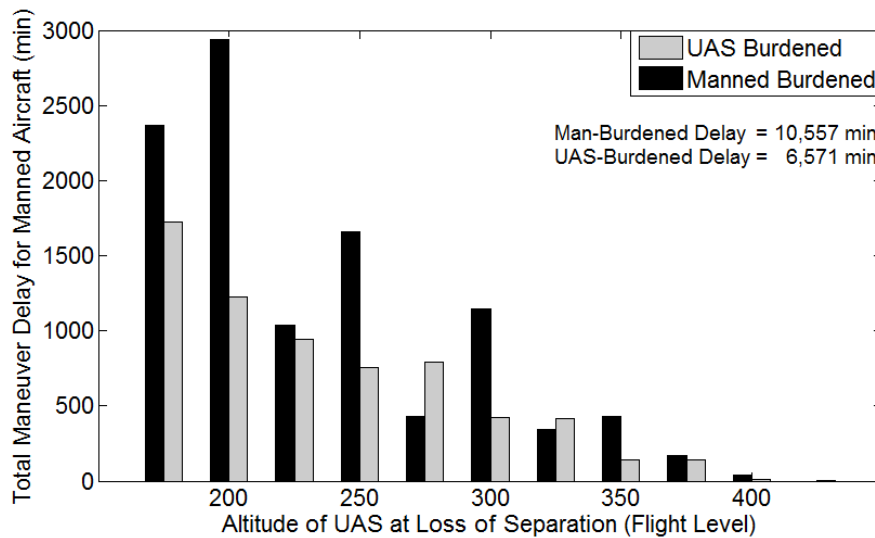


Figure 12. Manned aircraft delays as a function of burdened aircraft type and UAS altitude.

The results presented above include all separation requirements, from 5 to 30 nmi, because that large data set demonstrates the system-level trends. Those trends persist at the standard separation requirement of five nmi and the mitigation approach of burdening UAS becomes even more attractive. The reduction in number of conflicts for this smaller separation requirement is shown in Figure 13, which represents 40 UAS and 494 UAS flight hours for each of the burdening cases. Nearly all the manned resolutions were shifted to UAS in this condition, 125 of 134, and all but two of those resolved by manned aircraft were between FL200 and FL300. This case study shows that burdening UAS to resolve conflicts is particularly effective when the horizontal separation is small. While in the manned-burdened case a manned aircraft maneuvers every 3.7 UAS flight hours; when the UAS is burdened the rate drops to only one maneuver every 55 UAS flight hours. With an average delay per resolution of 80 sec (Figure 10), this means the manned aircraft incur a delay of only 1.5 s per UAS flight hour. This compares very favorably to the 8.8 s of delay incurred due to manned conflicts for every manned aircraft flight hour.

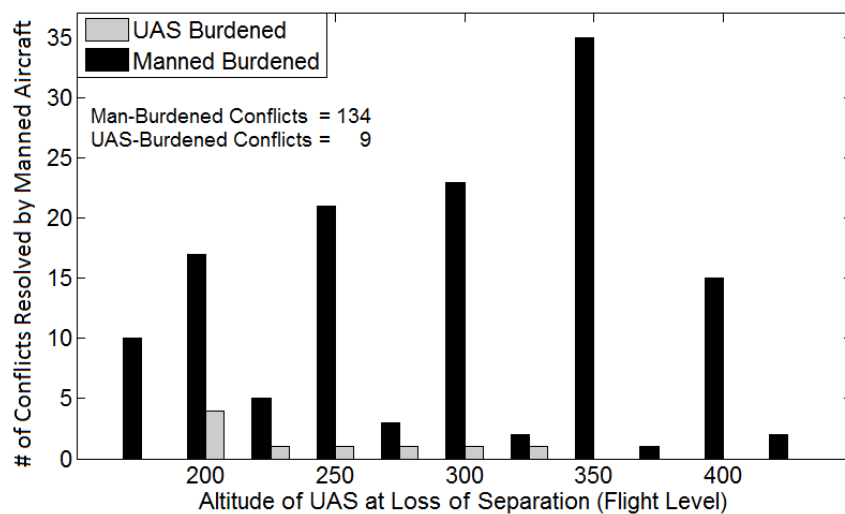


Figure 13. Manned aircraft maneuvers for 5nmi separation requirement as a function of burdened aircraft type and UAS altitude.

Table 8. Independent variables evaluated in Section Effectiveness of Mitigation Strategies: Speed

Experiment Variable	Conditions in Section	Values of Conditions Evaluated in Section
Mission	0	Fire monitoring, military training
UAS Cruise Altitude (FL)	5	200, 250, 300, 350, 400
UAS Cruise Speed (kn)	0	100, 150, 250, 350
Horizontal Separation for UAS (nmi)	4	5, 10, 20, 30
Conflict Resolution Time (min)	0	8, 14, 20
Burdened Aircraft Type	2	UAS, manned, neither

Effectiveness of Mitigation Strategies: UAS Speed Dependency

This section investigates the effectiveness of the two mitigation approaches in reducing the number and delay of manned aircraft resolution maneuvers as a function of UAS true airspeed (TAS) (see Table 8). The data suggest that burdening UAS may be effective in reducing the impact on manned aircraft, especially at higher UAS cruise speeds and lower horizontal separation requirements.

The number of conflicts resolved by manned aircraft as a function of burdened aircraft type and UAS TAS is shown in Figure 14. The corresponding delay that is reduced as a function of these variables is shown in Figure 15. In those figures the UAS are considered at their assigned cruise speed if within 4.8 kn of that value (100, 150, 250, 350 kn), and any speeds outside those ranges are plotted in between the four experimental conditions. UAS not flying at their assigned cruise speed are nearly always climbing or descending. Both the number of conflicts and their resulting total delay are concentrated at lower speeds, but as discussed in a previous section this increase is largely due to slow UAS being aloft for a longer period of time. The reduction in number of manned-executed maneuvers because of UAS burdening was 52% and the reduction in manned-aircraft delay 38%.

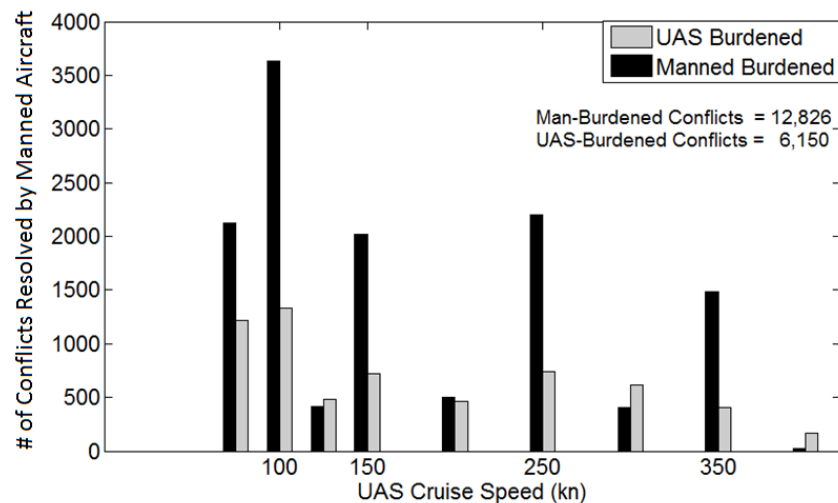


Figure 14. Manned aircraft maneuvers as a function of burdened aircraft type and UAS speed.

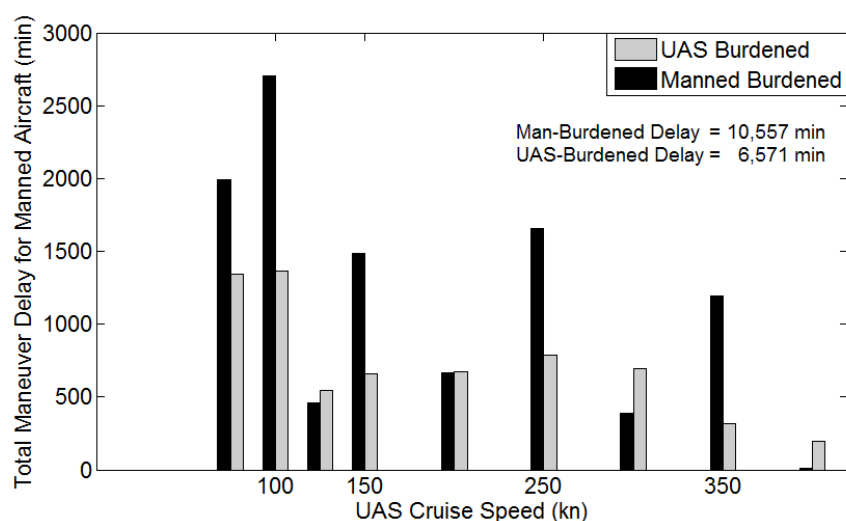


Figure 15. Manned aircraft delays as a function of burdened aircraft type and UAS speed.

Burdened UAS are able to resolve conflicts most frequently when separation buffers are low and UAS cruise speeds high. The reduction in impact to manned aircraft for the 5 nmi separation buffer is shown in Figure 16, with only nine conflicts that UAS were unable to resolve and all of those occurring at 150 kn or below. These are the same nine conflicts represented in Figure 13 that occurred between FL200 and FL300, requiring manned aircraft to maneuver only once per 55 UAS flight hours. The trend in UAS ability to resolve conflicts as a function of separation requirement and cruise speed are shown in Figure 17. This figure is key to understanding why increasing the separation requirement is ineffective in reducing conflict resolution maneuver delays of manned aircraft, but burdening UAS is effective. With large separation requirements, UAS, particularly those cruising at 100 or 150 kn, are unable to resolve up to 45% of their conflicts with manned aircraft. Higher speeds slightly improve the rate at which UAS burdening can reduce the number of conflicts requiring resolution by manned aircraft, but this effect cannot compensate for the much larger number of conflicts that occur with larger horizontal separation requirements.

The overall impact on manned-aircraft because of a larger separation requirement is indicated by cross referencing these results with Figure 9 and Figure 10. Not only are the UAS less frequently able to resolve their own conflicts at larger separation requirements (Figure 17), but there are up to 20 times as many conflicts overall (Figure 9) and each conflict delays the manned aircraft 8 times longer in comparison with the 5 nmi separation requirement (Figure 10). By requiring only 5 nmi of separation the UAS resolve more than 90% of their conflicts with manned aircraft even at the relatively slow Class A cruise speeds of 100 and 150 kn. These results indicate that a substantial reduction in en route conflict maneuver delay to existing traffic can be achieved by burdening UAS with the responsibility to execute conflict resolution maneuvers and maintain five nmi of separation from other aircraft. Additional studies, particularly human-in-the-loop experiments, will be required to ensure UAS are capable of responding to controller clearances predictably and reliably enough to accept this burden, or to develop procedures that allow UAS to assume responsibility for delegated separation.

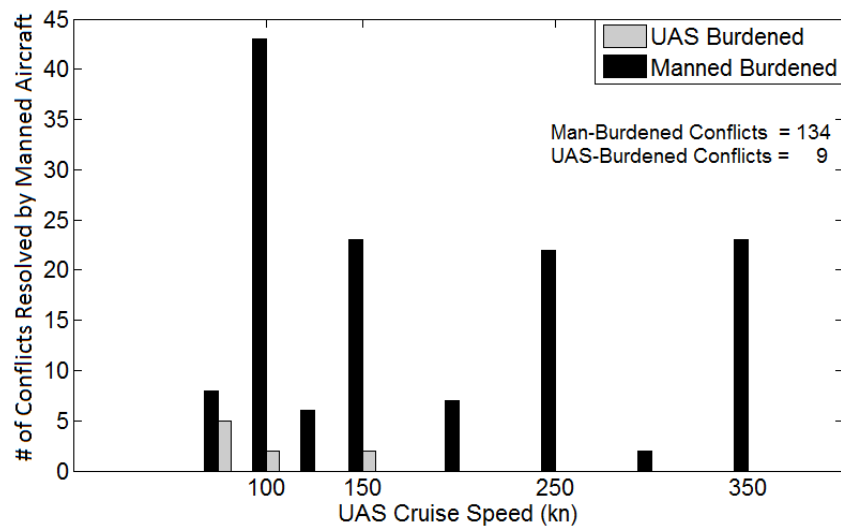


Figure 16. Manned aircraft maneuvers for 5nmi separation requirement as a function of burdened aircraft type and UAS speed.

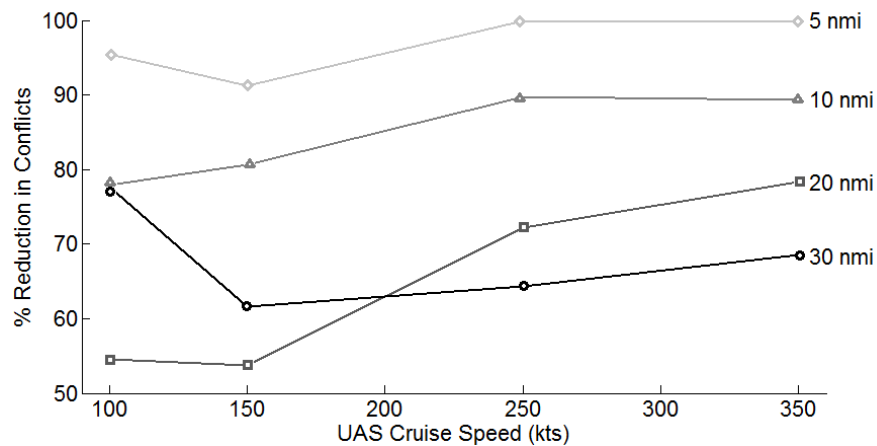


Figure 17. Percent reduction in number of conflicts resolved by manned aircraft because of UAS burdening, plotted as a function of horizontal separation requirement.

Conclusions

The impact to existing NAS traffic from 1440 medium-altitude, long-endurance UAS flights was studied in simulation. Impact was measured by the additional conflicts and conflict resolution maneuver delays created by the UAS flights. The cruise altitudes and speeds of the UAS were systematically varied to understand the effects of these independent variables on existing traffic. Two approaches to mitigating these effects were tested: larger horizontal separation buffers and burdening the UAS with executing conflict resolution maneuvers whenever they encounter manned aircraft.

UAS operations at lower en route cruise altitudes (between FL200 and 250) cause a disproportionately larger number of conflicts and resulting resolution delays for manned aircraft. This finding appears to be caused by transitioning of either manned aircraft or UAS through these altitudes that results in more disruptive encounters, particularly with aircraft transitioning to their arrival airports.

The cruise speed at which UAS operations are conducted does not appear to have a strong effect on existing NAS traffic. More conflicts are reported for slower-flying UAS, but the rate of conflicts per UAS flight hour is about the same or slightly lower than between existing traffic and higher-speed UAS. A benefit of integrating these slower UAS is that manned aircraft appear to incur less delay per conflict when they encounter UAS compared to conflicts with existing aircraft, only 9 s rather than 16 s. Conversely, when UAS cruise at higher speeds they are more readily able to solve conflicts with manned aircraft and therefore impose less delay overall on existing traffic.

Of the two mitigation approaches studied, burdening the UAS with executing conflict resolution maneuvers appears to be the most effective approach to reducing *overall delay* to existing traffic. With current en route horizontal separation standards of five nmi, UAS are able to resolve 93% of conflicts with manned aircraft. The rate of successful resolutions by UAS rises to 100% when their cruise speed is 250 kn or higher, or if they cruise at FL350 or above. The rate of conflicts between UAS and manned aircraft is one per 3.7 UAS flight hours with current separation requirements, but if the UAS is burdened then manned aircraft must execute a resolution only once per 55 UAS flight hours. The impact on existing traffic therefore seems to be nearly zero for UAS at higher altitudes and faster speeds, and quite minor even for lower altitudes and slower speeds. Additional research will be necessary to determine whether this approach is similarly feasible and beneficial from an air traffic controller perspective.

Increasing the separation buffer for UAS is not effective at reducing the impact on manned aircraft. Three problems are inherent to larger separation requirements for UAS: more UAS-manned conflicts occur, the delay incurred by manned aircraft per resolution is higher, and UAS are less able to resolve these types of conflicts. At the largest separation requirement tested (30 nmi) UAS are able to resolve only 35% of conflicts and they cause 100 times as many conflicts that are about 10 times as inefficient to resolve as conflicts under current separation requirements. The compound effect of these three problems is to increase the delay to manned aircraft from 1.5 seconds per UAS flight hour at five nmi to 57 seconds and 170 seconds per UAS flight hour at 20 and 30 nmi, respectively. In contrast, manned aircraft create only 8.8 s of delay per flight hour. An intriguing result worth further study is that conflicts between manned aircraft and UAS with a separation of 10 nmi appears to cause only as much delay (19 s) as a conflict between two manned aircraft with a 5 nmi requirement (16 s), probably because of the slower UAS speeds. This larger separation requirement, however, does create three times as many conflicts as the current requirement. Rather than increasing separation requirements beyond 10 nmi for UAS to compensate for communication and maneuvering latencies, UAS should comply with the same response time requirements as manned aircraft.

This research experiment has uncovered several additional questions that warrant further investigation. Principally, the concept of burdening UAS to resolve all conflicts with manned aircraft requires more detailed study. That conclusion is based only on the reduction of total conflict resolution delay to manned aircraft, not the impact on UAS mission success, the ability of controllers to safely meet this requirement, or the evaluation of alternative methods to reduce NAS impact, all of which would need thorough investigation before such a dramatic requirement could be recommended. The encounter and delay metrics should be calculated for many additional UAS missions at new combinations of speed and altitude not investigated here. Those studies should confirm the result that encounters with vertically transitioning aircraft present the most difficult conflict situations for slow UAS to resolve, especially when the UAS is traveling at slower speeds. They should also attempt to replicate the result that slower UAS cause less delay per conflict for manned aircraft, and they should

compare the workload imposed on controllers to resolve these conflicts with more typical conflict situations between two manned aircraft. It may be worthwhile to further study the impact of a 10 nmi horizontal separation requirement for UAS because of the delay results measured here, however procedural and human factors impacts of such a requirement will probably render that mitigation technique impractical. Finally, the impact of other typical UAS performance characteristics, like slower turn or climb rates, should be evaluated.

Acronyms

AAC	Advanced Airspace Concept
ACES	Airspace Concept Evaluation System
ASDI	Aircraft Situation Display to Industry
BADA	Base of Aircraft Data
FL	flight level
LOS	loss of separation
NAS	National Airspace System
RVSM	reduced vertical separation minimum
SAA	sense and avoid
TAS	true airspeed
TRACON	terminal radar approach control ?
UAS	unmanned aircraft systems

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